# Radiation Dose Assessments of Solar Particle Events with Spectral Representation at High Energies for the Improvement of Radiation Protection


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# Solar Proton Spectra for Radiation Analysis

## Functional Forms with Measurements up to 100 MeV

- Exponential in Rigidity[1] : $\Phi(>R)=J_0 \exp(-R/R_0)$
- Exponential in Energy[2] : $\Phi(>E)=J_0 \exp(-E/E_0)$
- Sum of Two Exponentials[3,4] : $\Phi(>E)=J_1 \exp(-E/E_1) + J_2 \exp(-E/E_2)$
- Weibull Fuction in Energy[5,6] : $\Phi(>E)=J_0 \exp(- \kappa E^{\alpha})$

These spectral representations are also correct for high energies?


[1]Freier PS and Webber WR*, J. Geophysical Research*, **68**(6), 1605-1629, 1963.

[2]King JH, *J. Spacecraft*, **11**(6), 401-408, 1974.

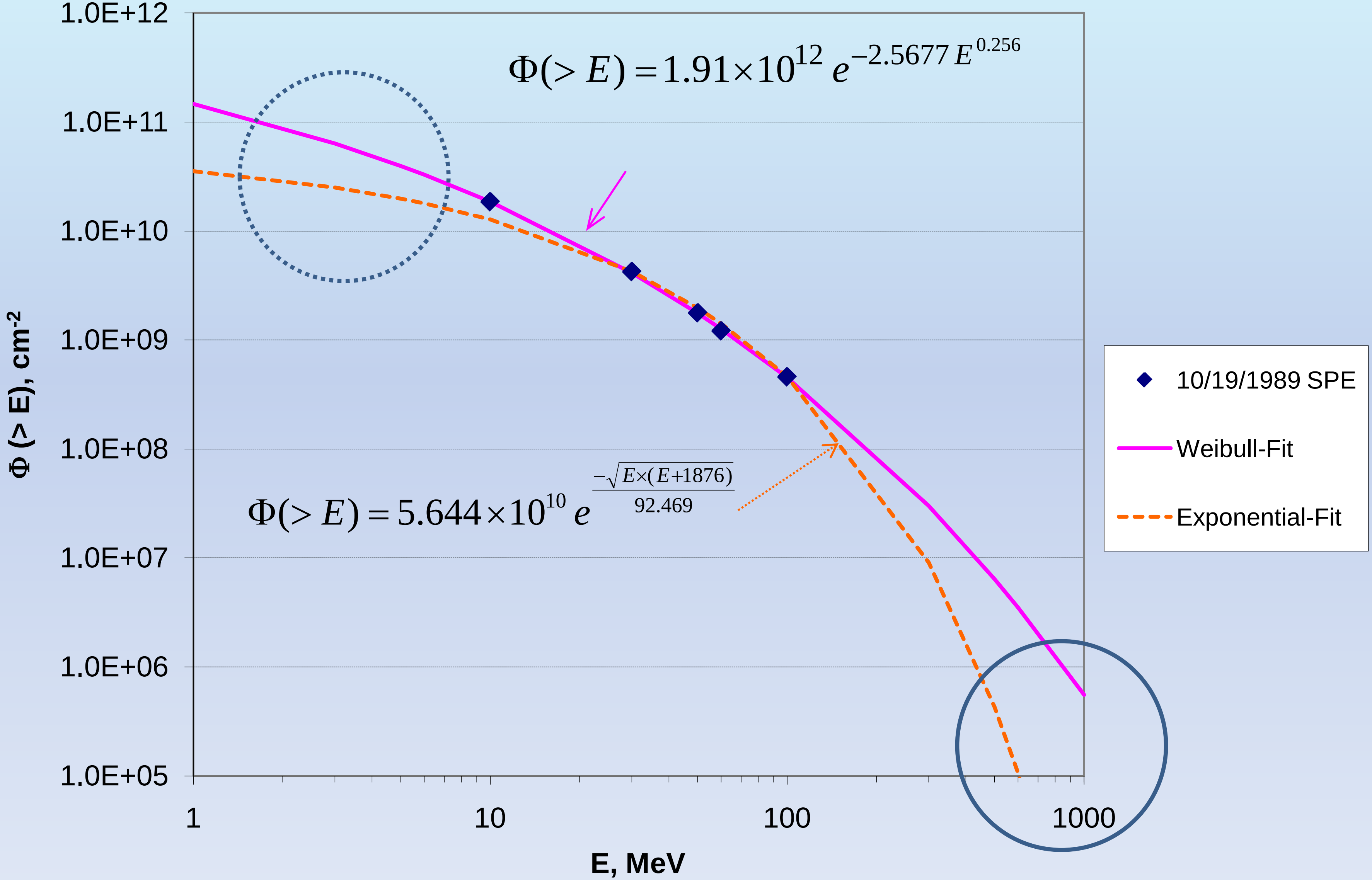
[3]BRYNTRN: Cucinotta FA, Wilson JW, Badavi FF., Washington, DC: NASA; Report No. TP-3472; 1994.

[4]HZETRN: Wilson JW, Townsend LW, Schimmerling W, Khandelwal GS, Khan F, Nealy JE, Cucinotta FA, Simonsen LC, Shinn JL, Norbury JW., Washington, DC: NASA; Report No. RP-1257; 1991.

[5]Xapsos MA, Barth JL, Stassinopoulos, *et al*., *IEEE Trans. Nuc. Sci.* **47**(6), 2218-2223, 2000.

[6]Kim MY, Cucinotta FA, Wilson JW., Radiation and Environmental Biophysics, **46**(2), 95–100; 2007.

# Fit to Proton Fluence Measurements up to 100 MeV for Continuous Energy Spectrum



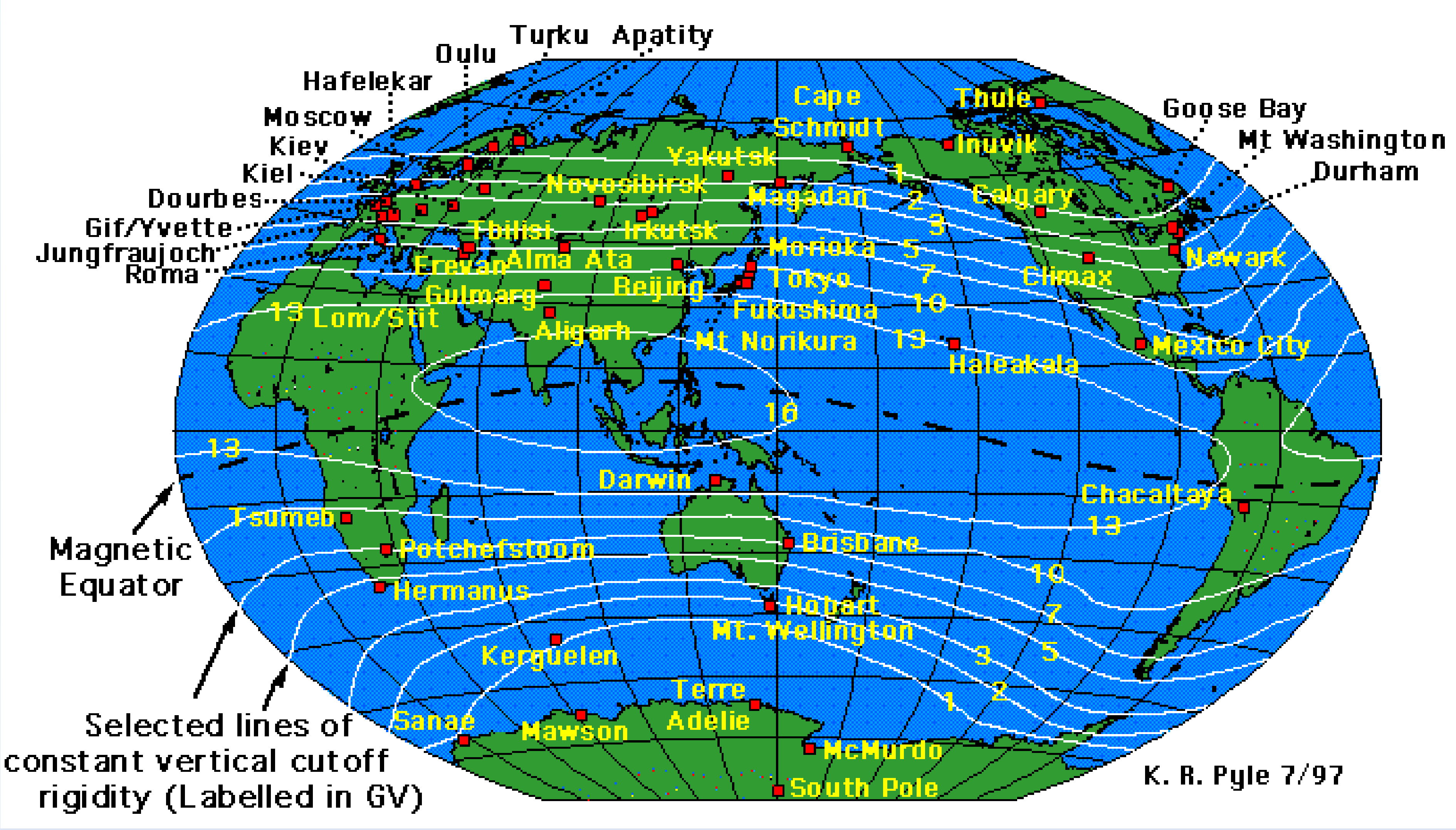
# Solar Proton Spectra for Radiation Analysis of SPE

Ground-Level Enhanced (GLE) events observed the from world-wide neutron monitor (NM) network for proton spectra above ~430 MeV (1 GV) :  66 GLEs have been observed since 1956.

→ Functional form of *Band function fit (a double power law in rigidity) based on the combined measurements from ~10 MeV to ~10 GeV for accurate solar proton spectra.

*Band D, et al., *Astrophys. J.*, **413**, 281-292, 1993.

# World-Wide Neutron Monitor (NM) Network Map




Source: Neutron Monitor Program, Bartol Research Institute, U. of Delaware

# World-Wide Neutron Monitor (NM) Network

Converting NM Data to Absolute Normalized Fluence Measurements:

- Each station at a geographical position → a characterization of the flux of charged particles arriving at the magnetosphere (arrival direction and rigidity/energy).
- The combination of NMs with the Earth's atmosphere and magnetosphere → a unique instrument with directional and energy resolution.
- Advantage of the use of all stations as a unified multidirectional detector → Substantially higher (< 0.1% for hourly data) accuracy than for a single instrument.

New Technique (Tylka and Dietrich, 2009)[7] for Analyzing GLE NM Data:

- Pressure-corrected data from the world-wide NM network
- Yield functions (Clem and Dorman, 2000)[8]
- Cutoff code "RcUT3" (Smart et al., 2006)[9]
- Altitude correction (McCracken, 1962)[10]

→Absolute Normalization and Spectral Index

[7]Tylka AJ and Dietrich WF, Proceedings of the 31st International Cosmic Ray Conference, Lodz, Poland, July 7-15, 2009.

[8]Clem JM and Dorman LI, *Space Sci. Rev.,* 93, pp. *335*-359, 2000.

[9]Smart DF, et al., *ASR,* 37, pp. 1206-1217, 2006.

[10]McCracken KG, *JGR,* 67, pp. 423-458, 1962.

# Functional Form of Event-Integrated GLE Proton Spectra for Radiation Analysis of Large SPEs

## Band Function with 4 Parameters ($J_0$, $\gamma_1$, $\gamma_2$, $R_0$): Double Power Law in Rigidity

$$\Phi(>R) = J_0 R^{-\gamma_1} e^{-R/R_0} \qquad \text{for } R \le (\gamma_2 - \gamma_1) R_0$$

$$\Phi(>R) = J_0 R^{-\gamma_2} \left\{ \left[ (\gamma_2 - \gamma_1) R_0 \right]^{(\gamma_2-\gamma_1)} e^{(\gamma_1-\gamma_2)} \right\} \qquad \text{for } R \ge (\gamma_2 - \gamma_1) R_0$$

## Differential Energy Spectra of Band Function

$$\frac{d\Phi}{dE} = \frac{d\Phi}{dR}\frac{dR}{dE} = \left( J_0(\gamma_1) R^{-\gamma_1 - 1} e^{-R/R_0} + J_0(\gamma_1) R^{-\gamma_1} \left( -\frac{1}{R_0} \right) e^{-R/R_0} \right) \frac{dR}{dE}$$

$$= J_0\, e^{-R/R_0} \left( \frac{\gamma_1}{R} + \frac{1}{R_0} \right) R^{-\gamma_1} \frac{dR}{dE} \qquad \text{for } R \le (\gamma_2 - \gamma_1) R_0$$

$$\frac{d\Phi}{dE} = \frac{d\Phi}{dR}\frac{dR}{dE} = J_0(\gamma_2) R^{-\gamma_2 - 1} \left\{ \left[ (\gamma_2 - \gamma_1) R_0 \right]^{(\gamma_2-\gamma_1)} e^{(\gamma_1-\gamma_2)} \right\} \frac{dR}{dE} \qquad \text{for } R \ge (\gamma_2 - \gamma_1) R_0$$

$$\frac{dR}{dE} = 10^{-3} \frac{A}{Z \times \beta(E)}$$

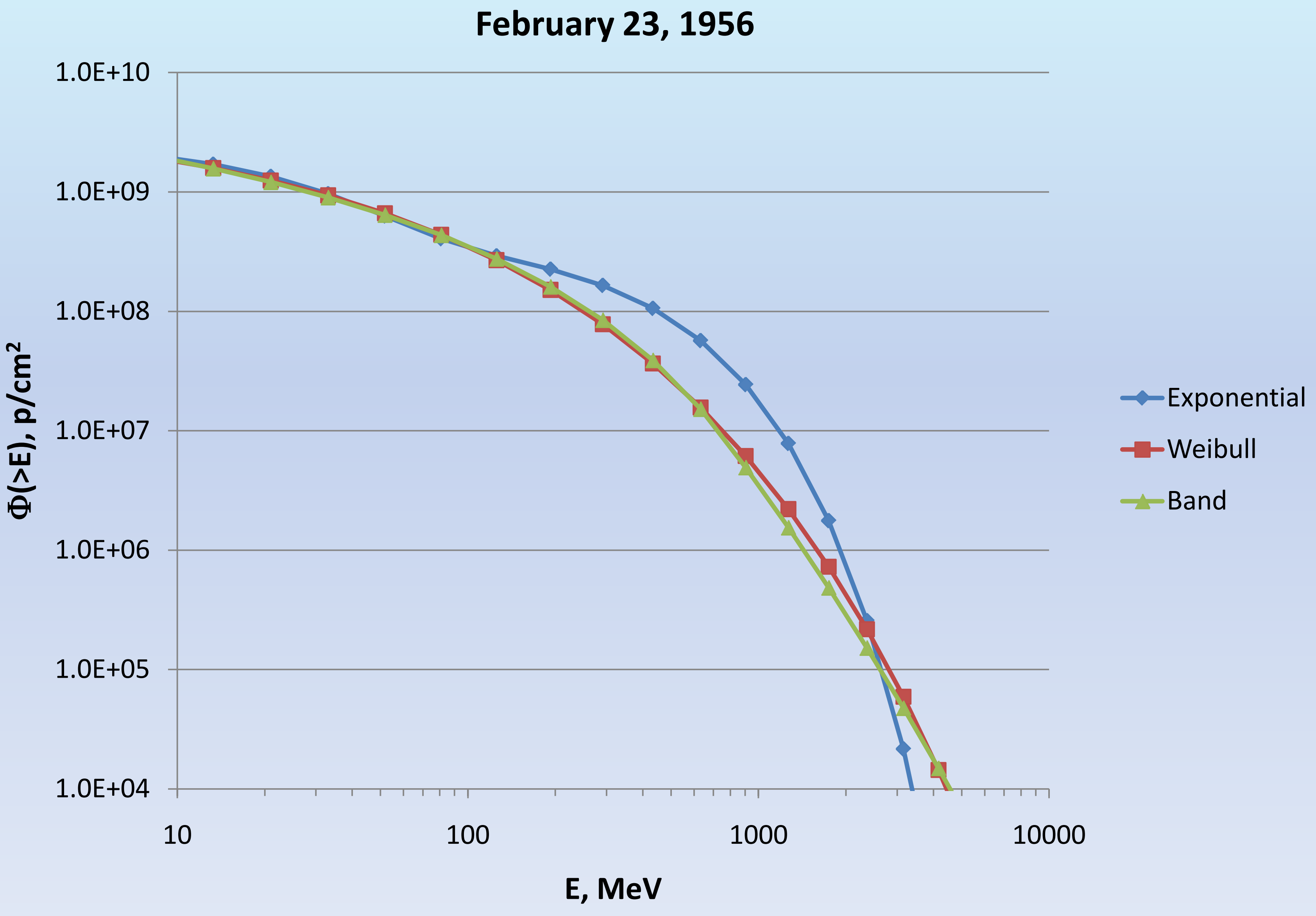
Where,
$R$ in GV, $E$ in MeV, and $\beta(E)$ is the proton velocity relative to the speed of light.

# GLE SPE Spectrum Comparison:

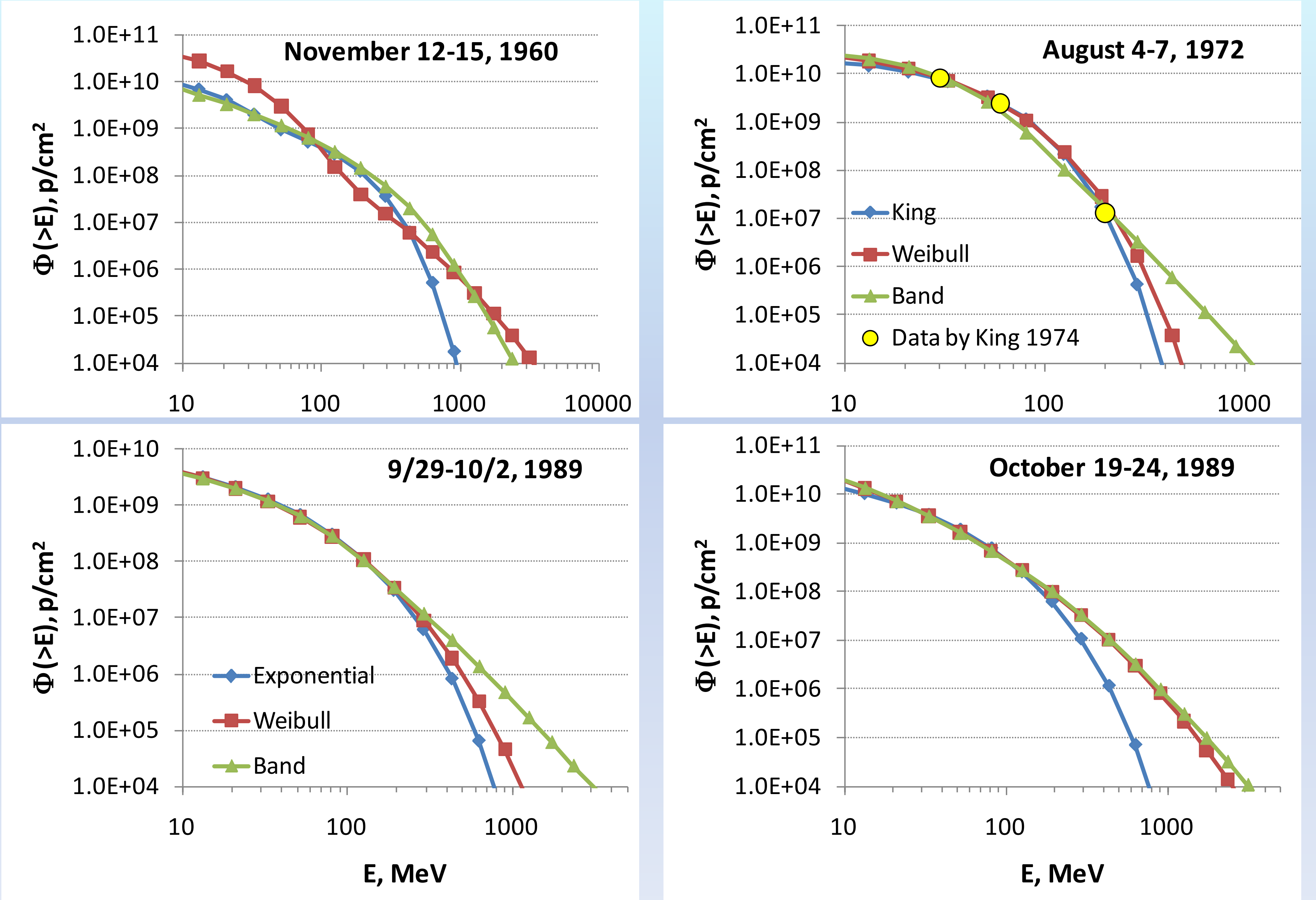
## Exponential, Weibull, & Band Functions

Feb 1956
Nov 1960
Aug 1972
Sept 1989
Oct 1989

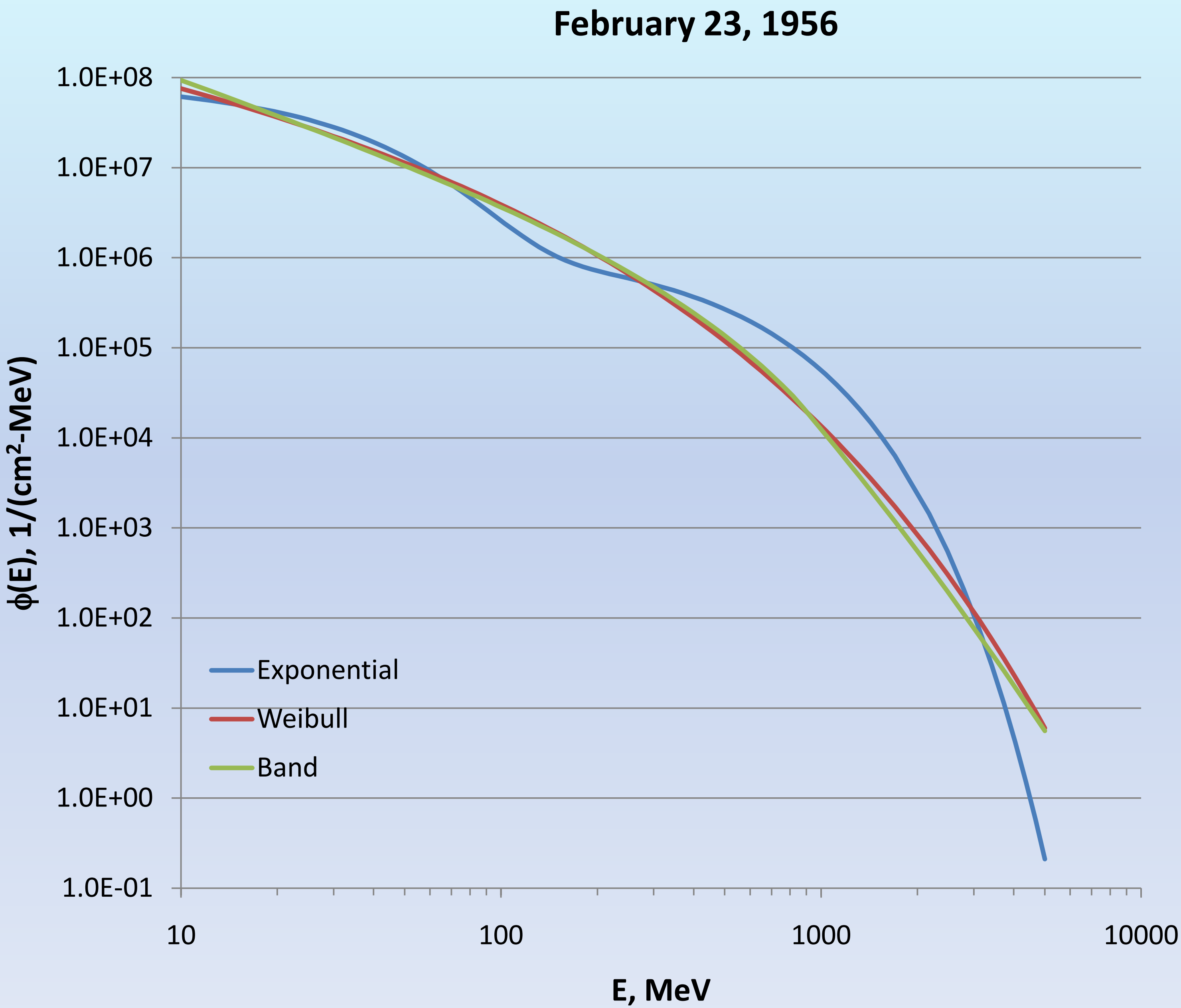
# Event-Integrated Integral Energy Spectra



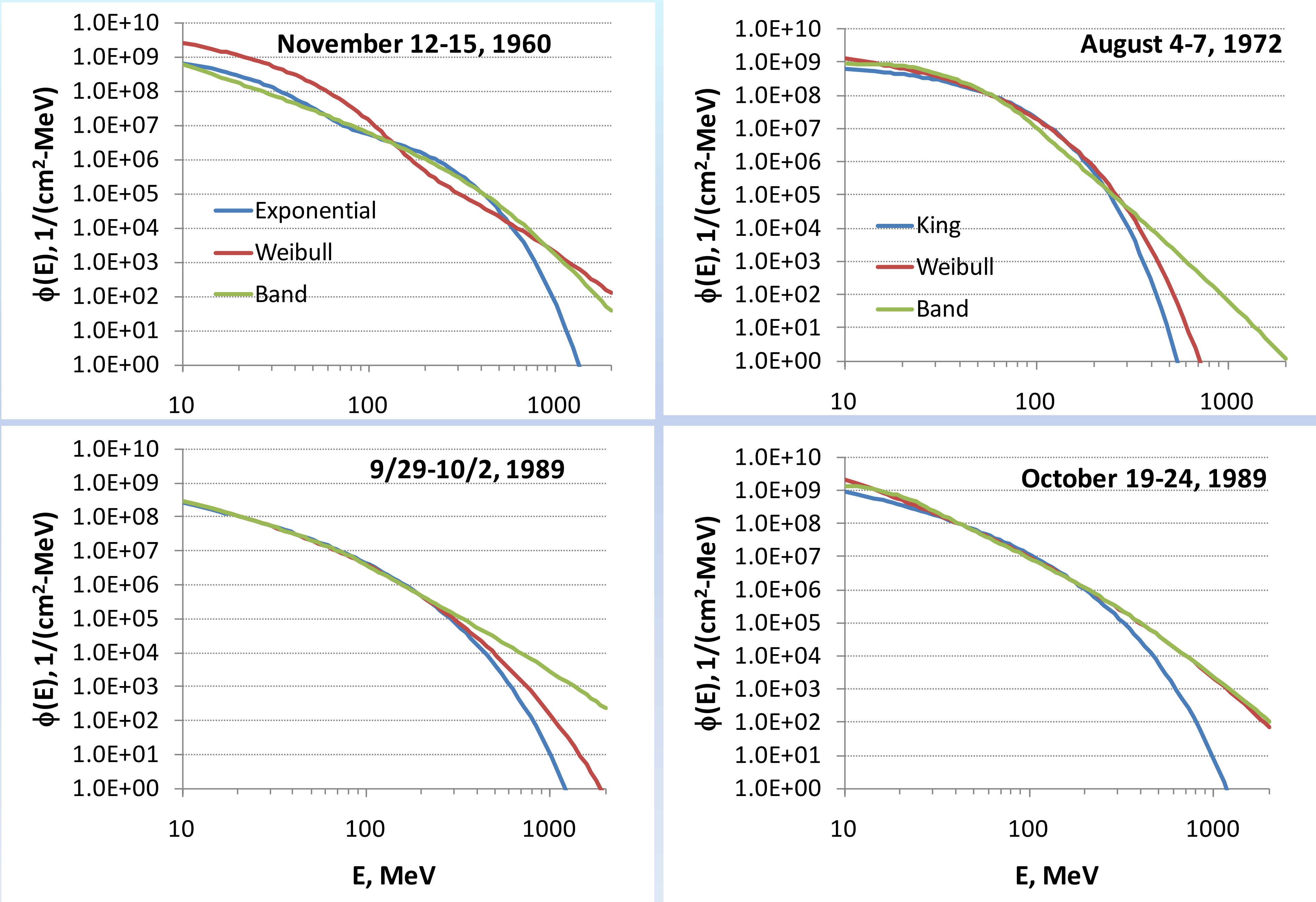
# Event-Integrated Integral Energy Spectra



# Event-Integrated Differential Energy Spectra



# Event-Integrated Differential Energy Spectra



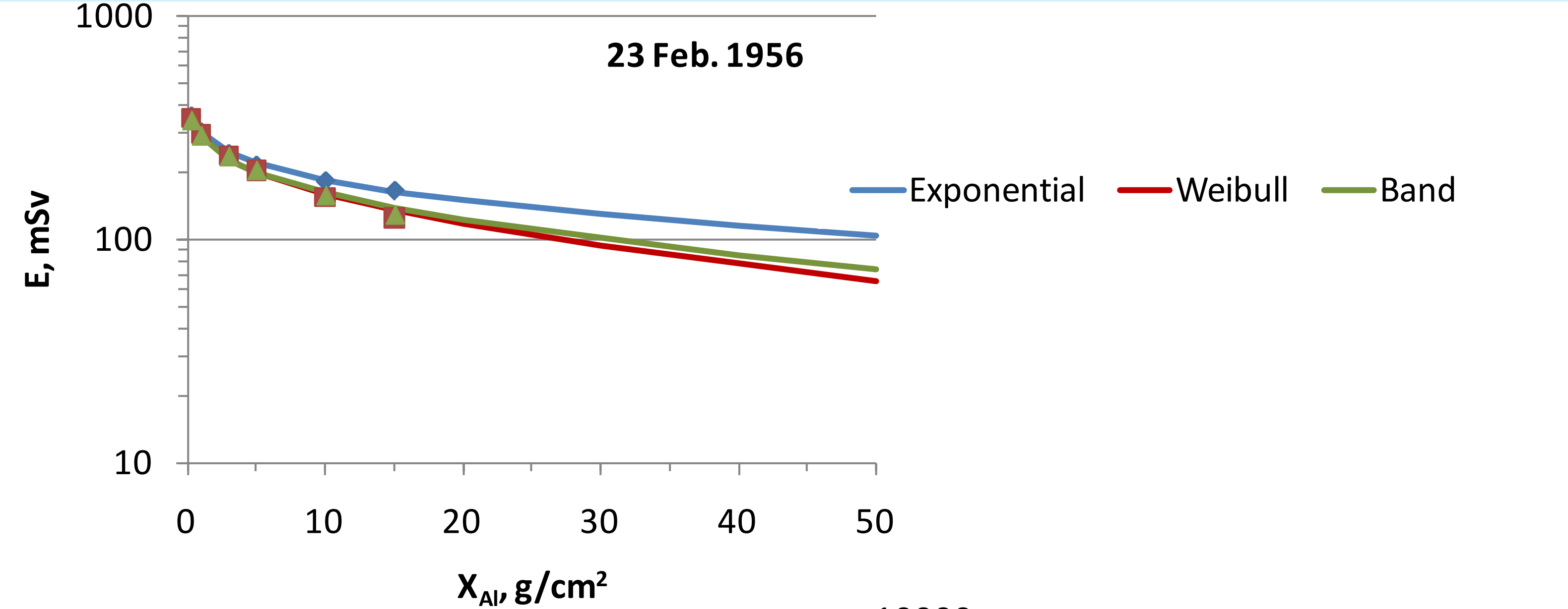
# Tissue Weighting Factors (ICRP 2007)

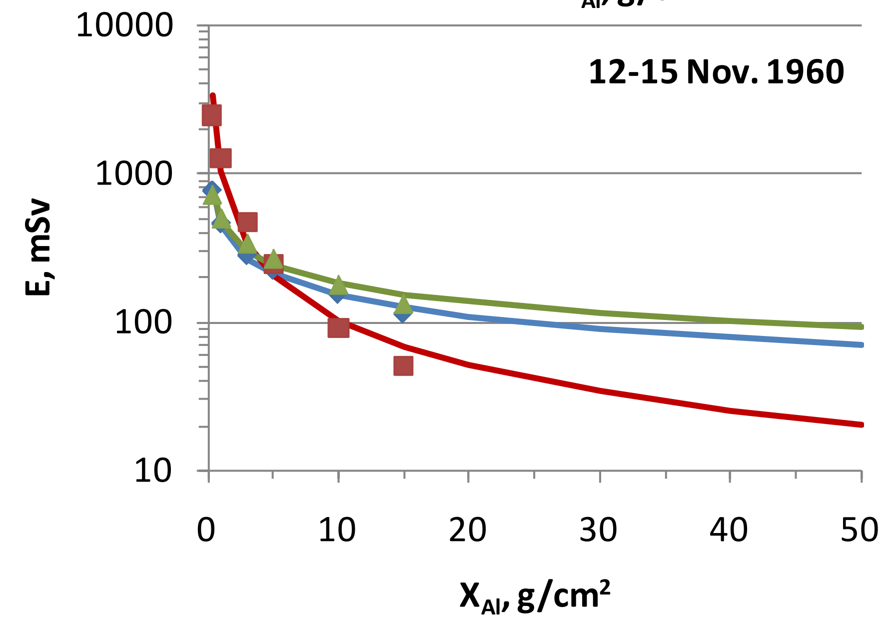
$$E = \sum_{\mathrm{T}} w_{\mathrm{T}} H_{\mathrm{T}}$$

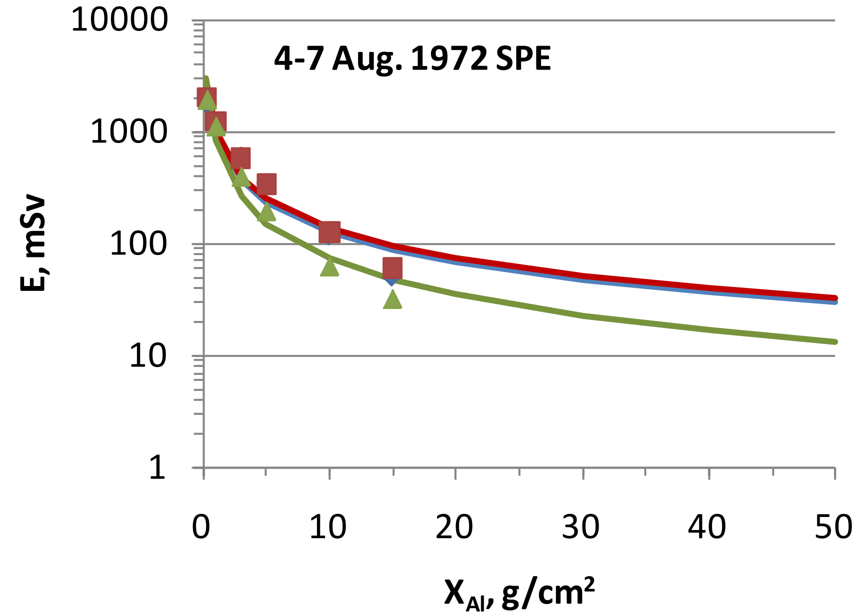
| Tissue/organ | $w_T$ | $\sum w_T$ |
|---|---|---|
| Bone-marrow, Lung, Stomach, Breast, Remainder Tissues* | 0.12 | 0.72 |
| Gonads | 0.08 | 0.08 |
| Bladder, Esophagus, Liver, Thyroid | 0.04 | 0.16 |
| Bone surface, Brain, Salivary glands, Skin | 0.01 | 0.04 |

*Remainder Tissues: Adrenals, Extrathoracic (ET) region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate, Small intestine, Spleen, Thymus, Uterus/cervix.

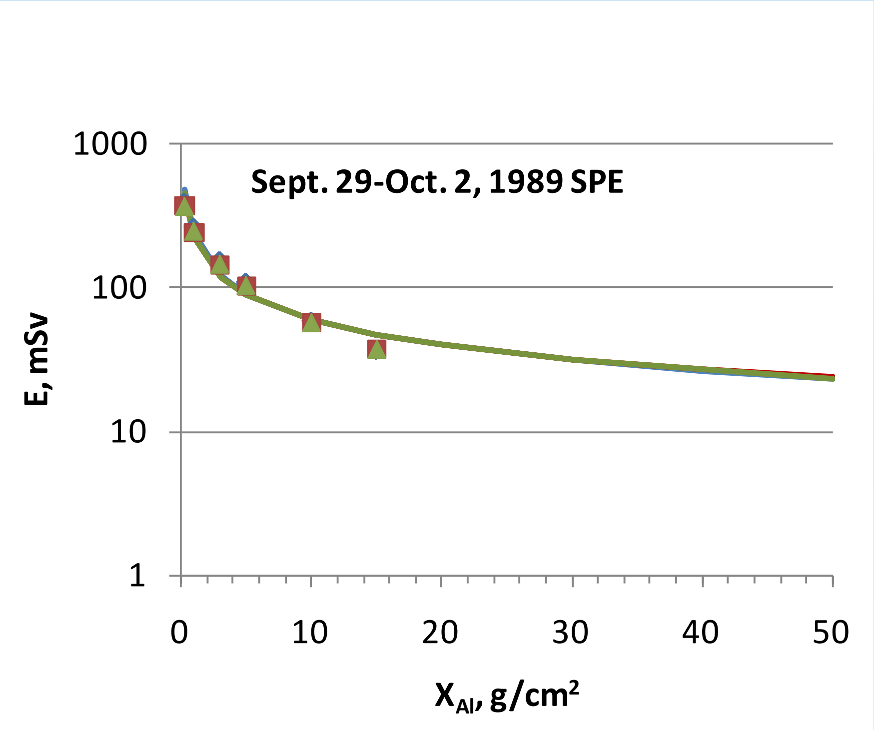
# Effective dose (mSv) for male crew members on the Lunar Surface

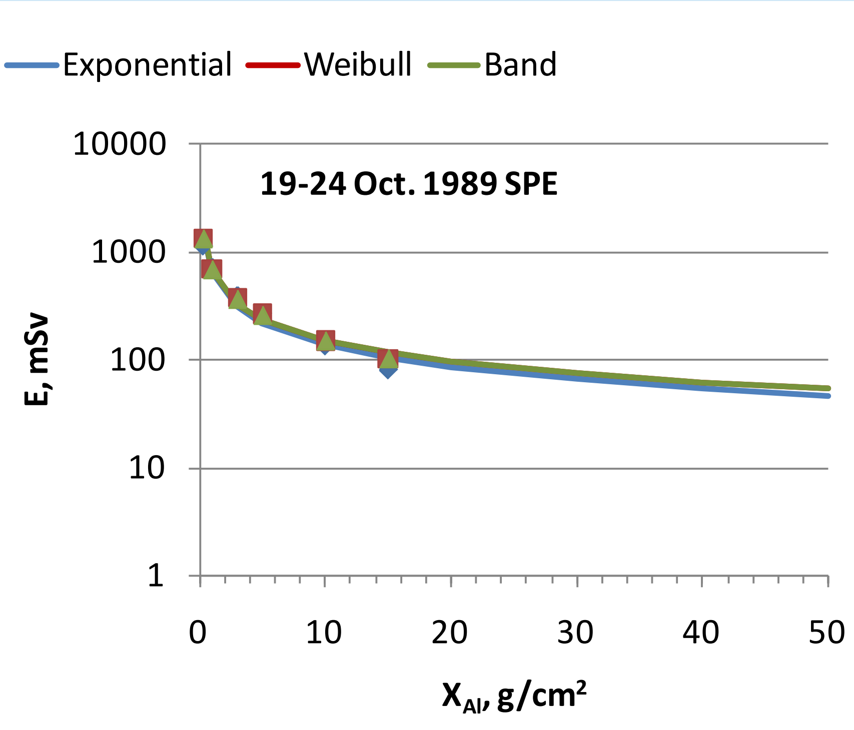


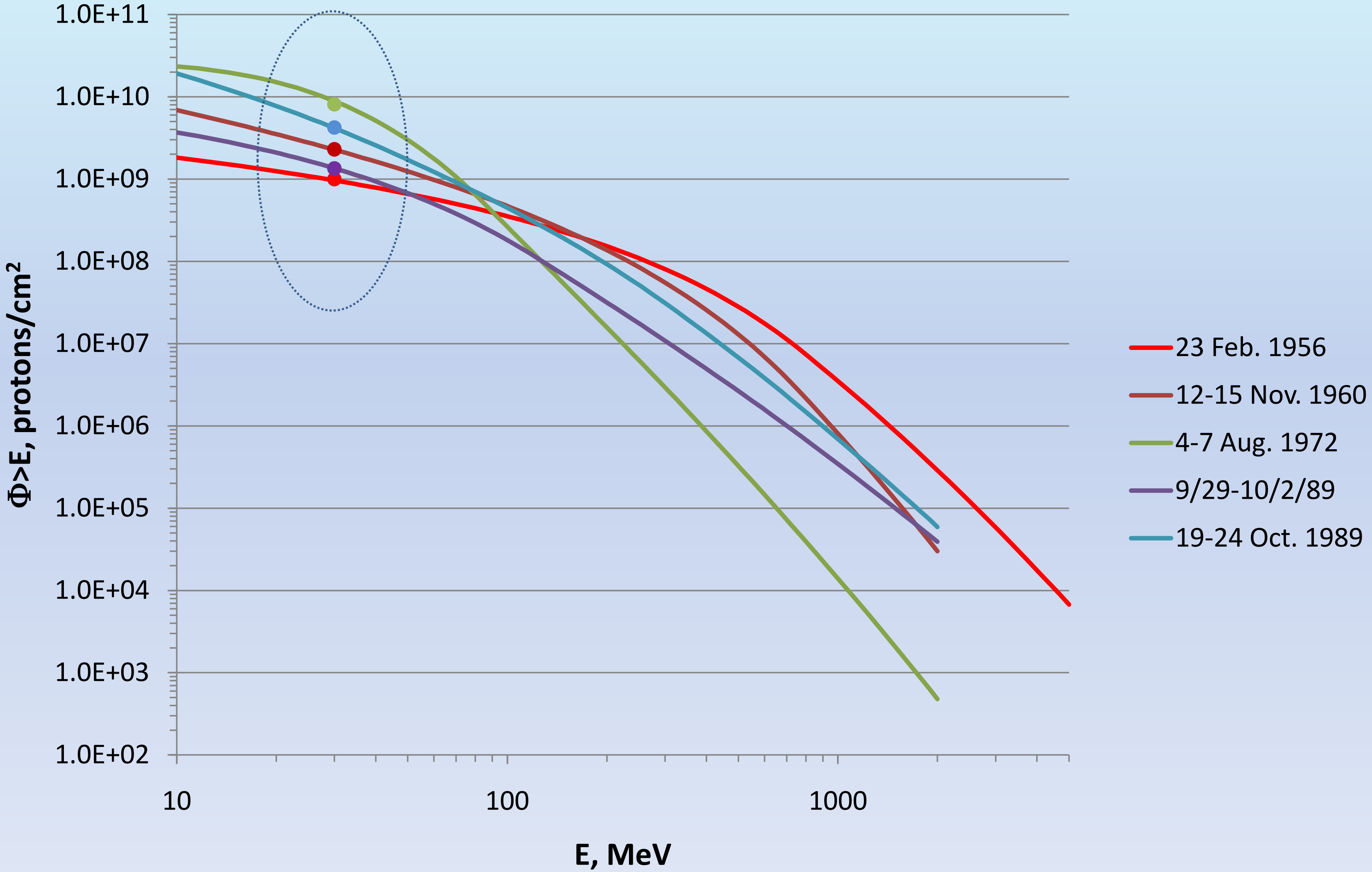



# Effective dose (mSv) for male crew members on the Lunar Surface

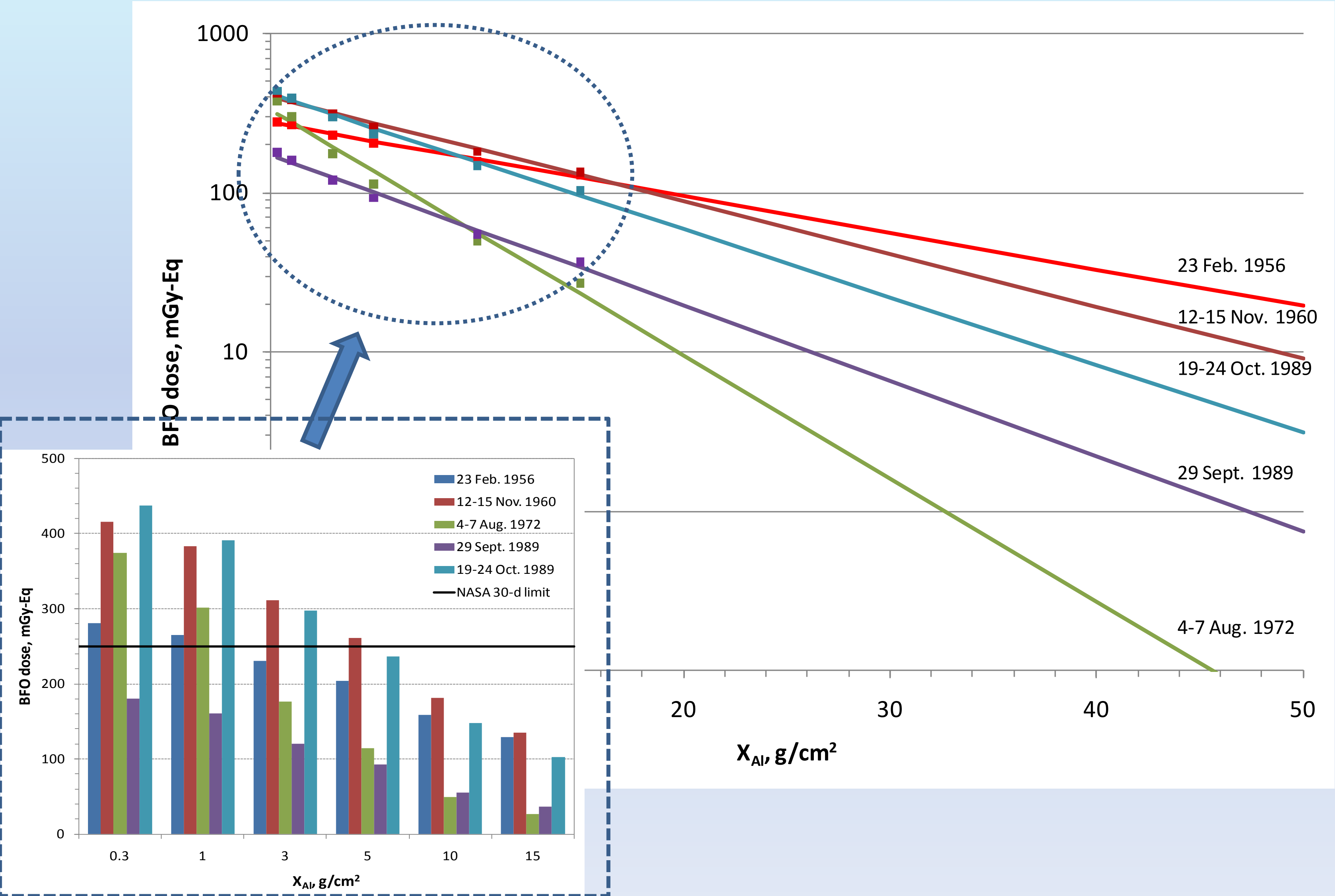


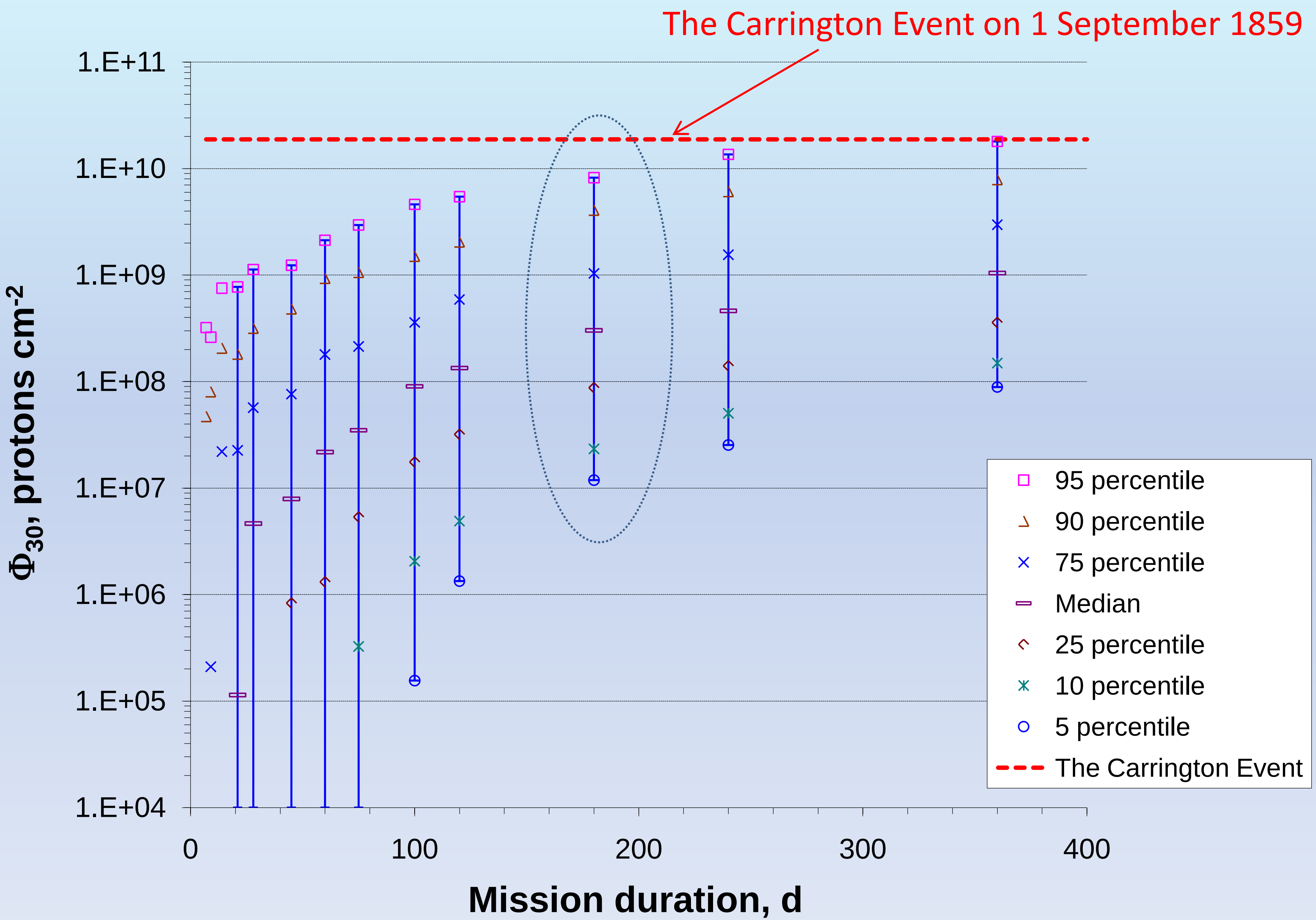
# Proton Spectra with Spectral Representation at High Energies: Band Function Fit



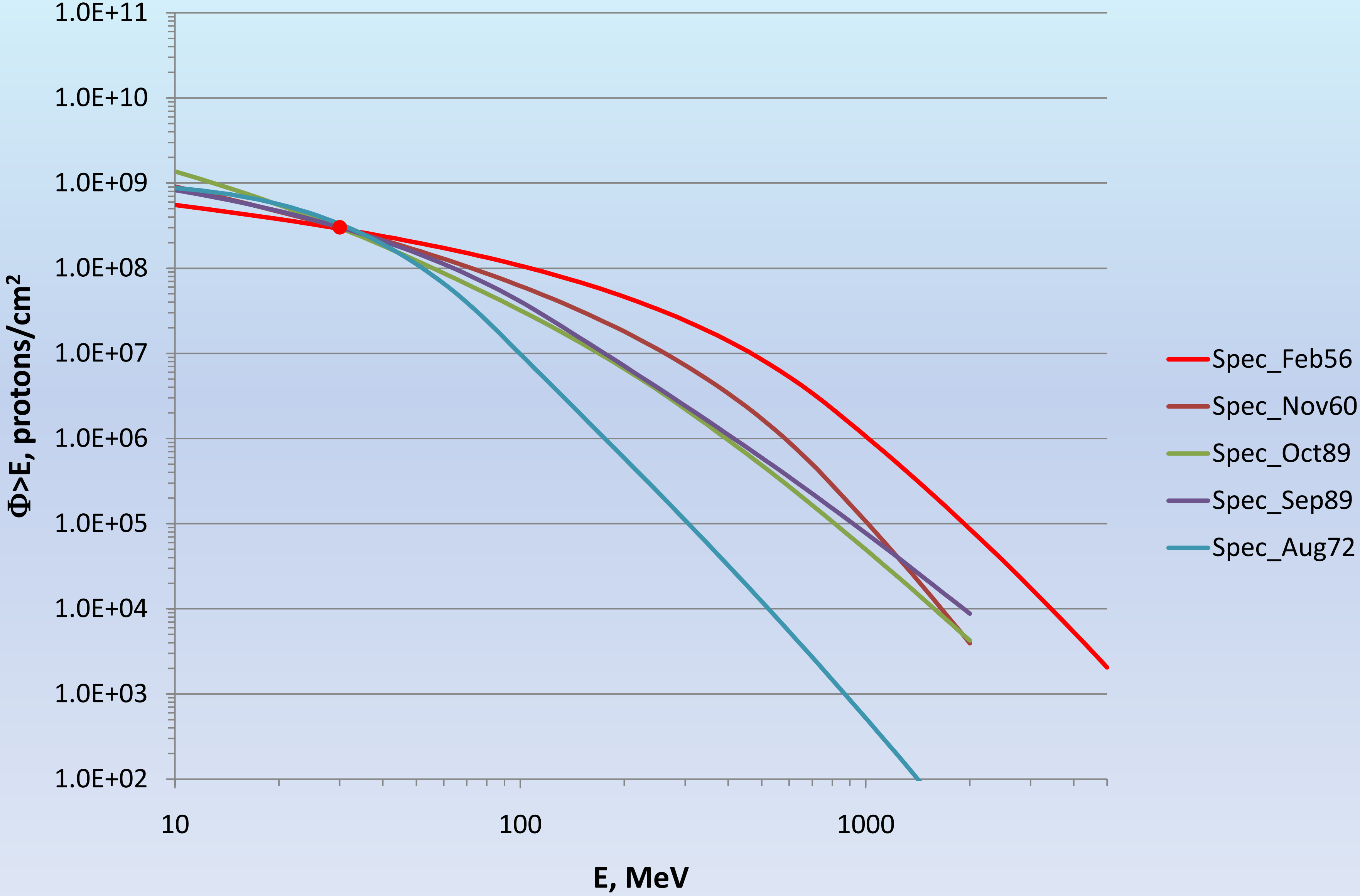
# BFO dose for Males on the Lunar Surface
# SPEs with Spectral Representations at High Energies



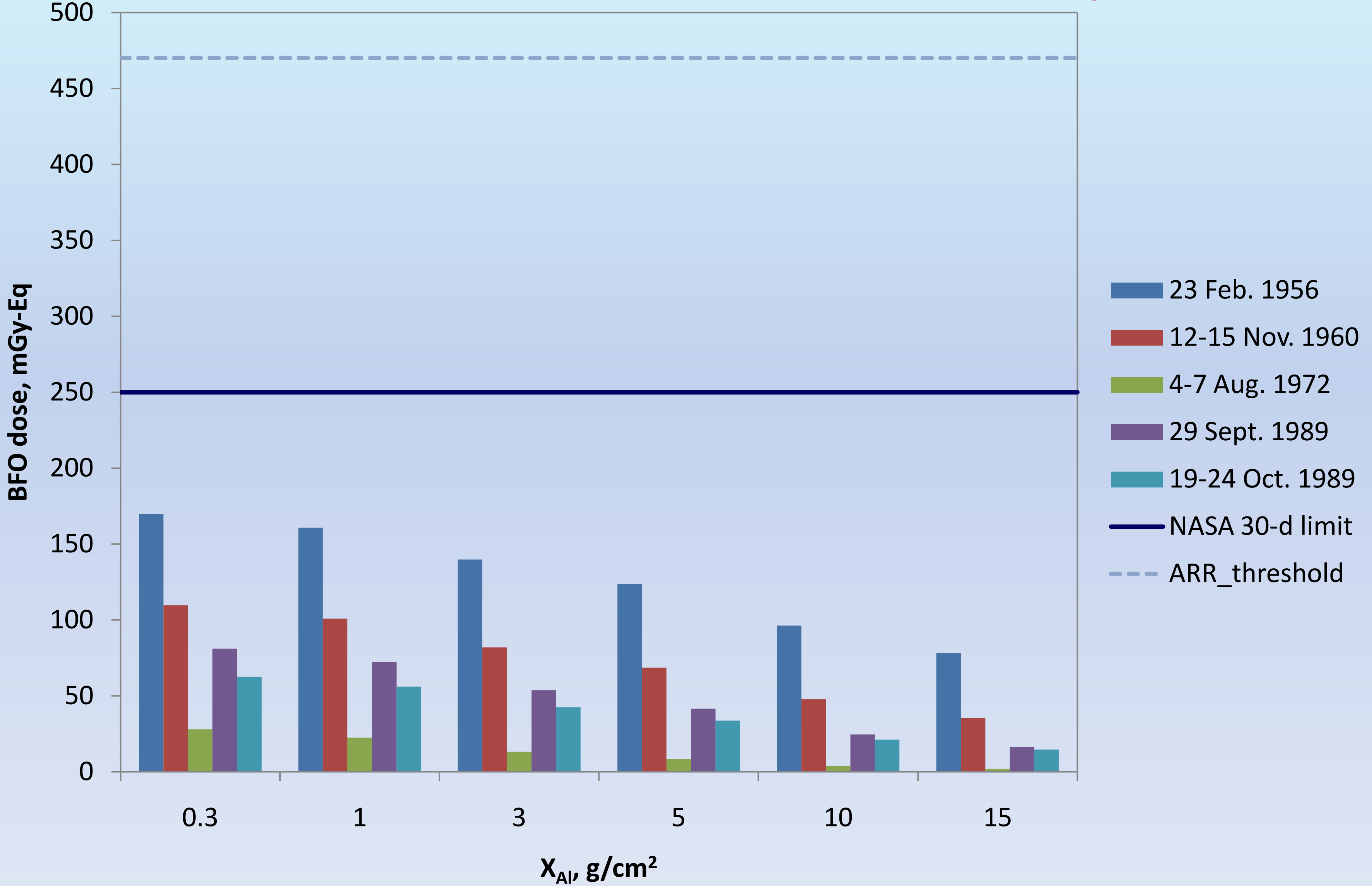
# Simulated Distribution of $\Phi_{30}$ for Mission Period



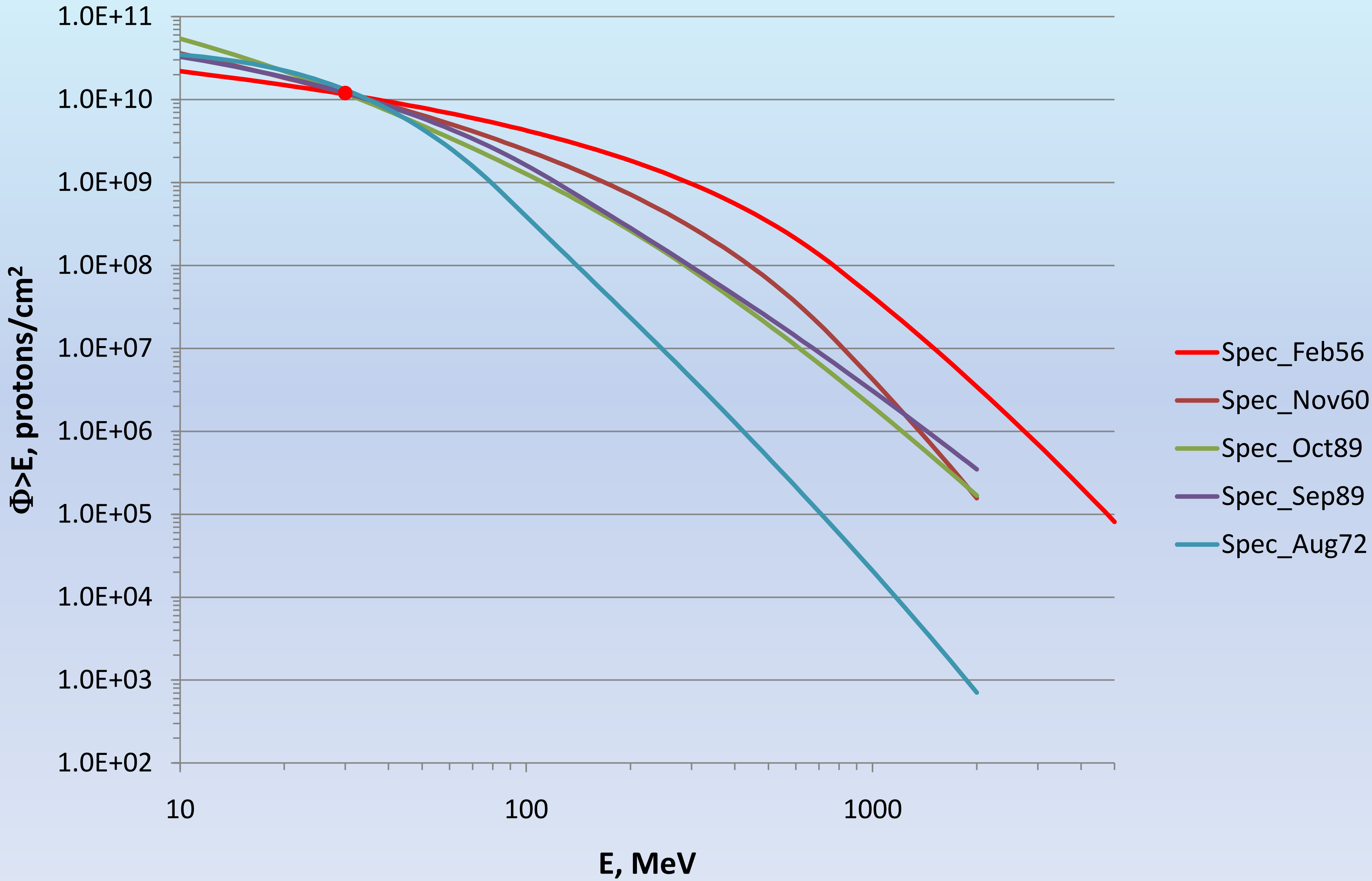
# Proton Spectra at the Median Fluence of 180-d with Various Band Function Fits



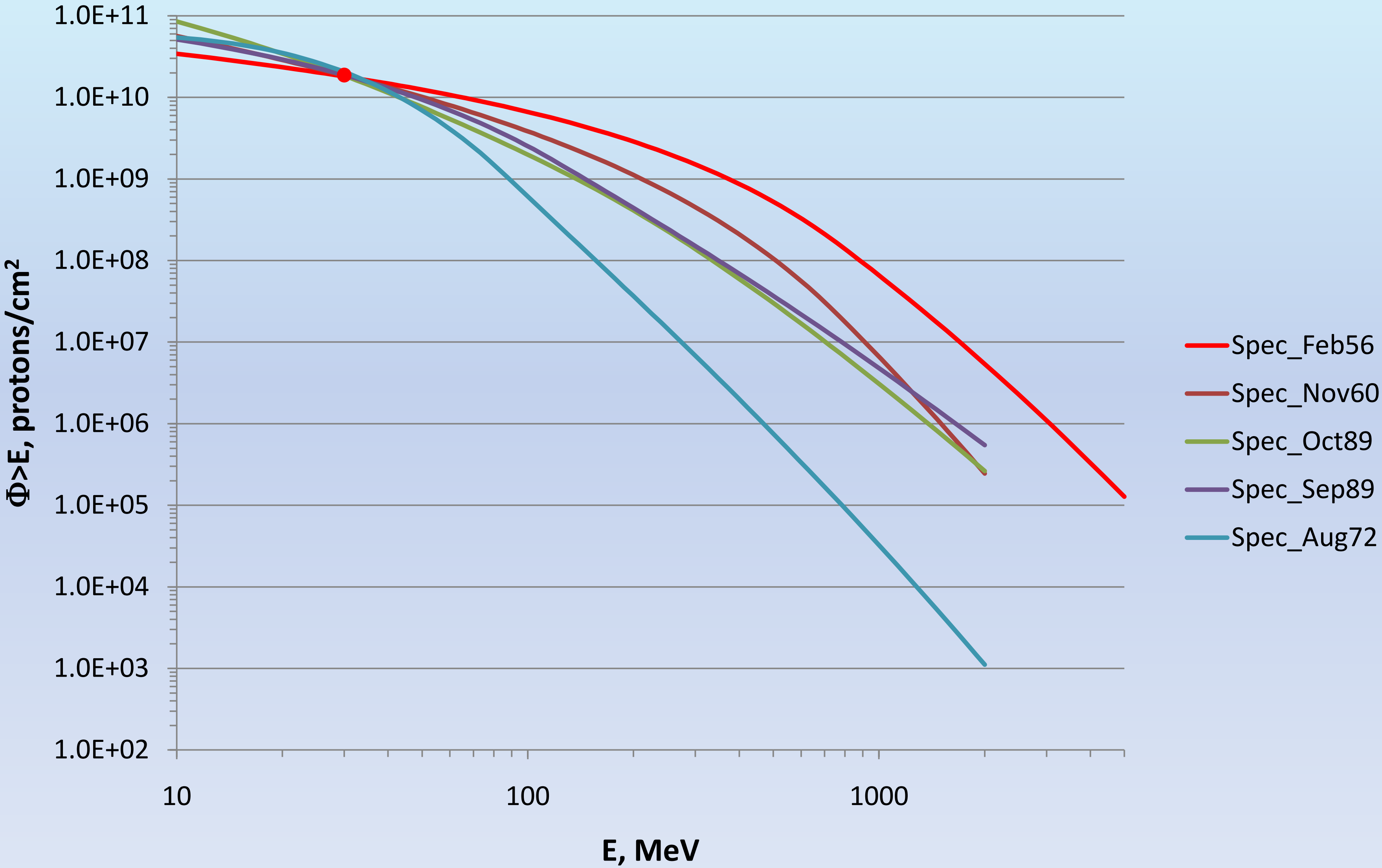
# BFO dose for Males for 180-d Interplanetary Space with the Median Fluence of GLE SPE Spectra



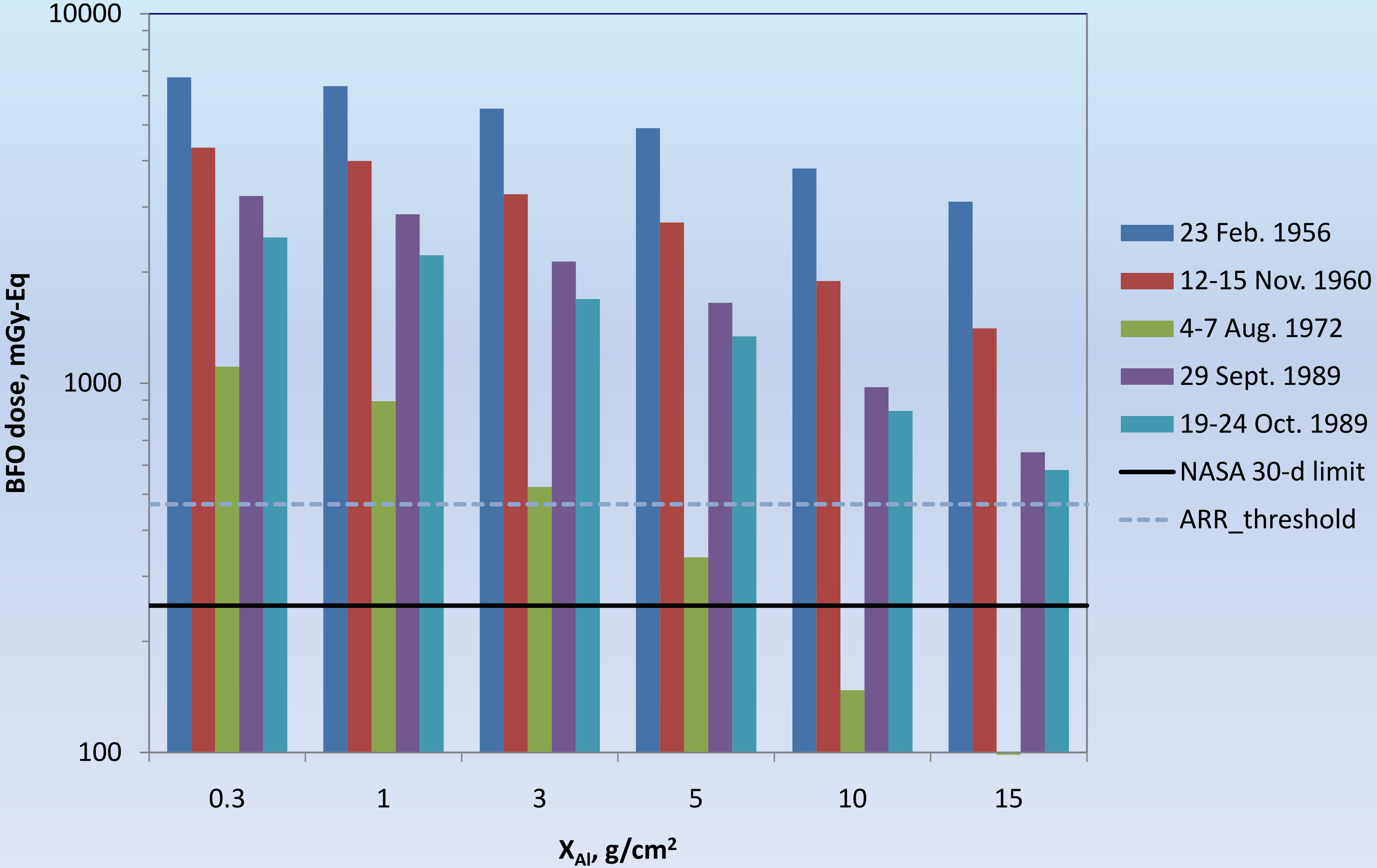
# Proton Spectra at the Upper 95% Fluence of 180-d with Various Band Function Fits



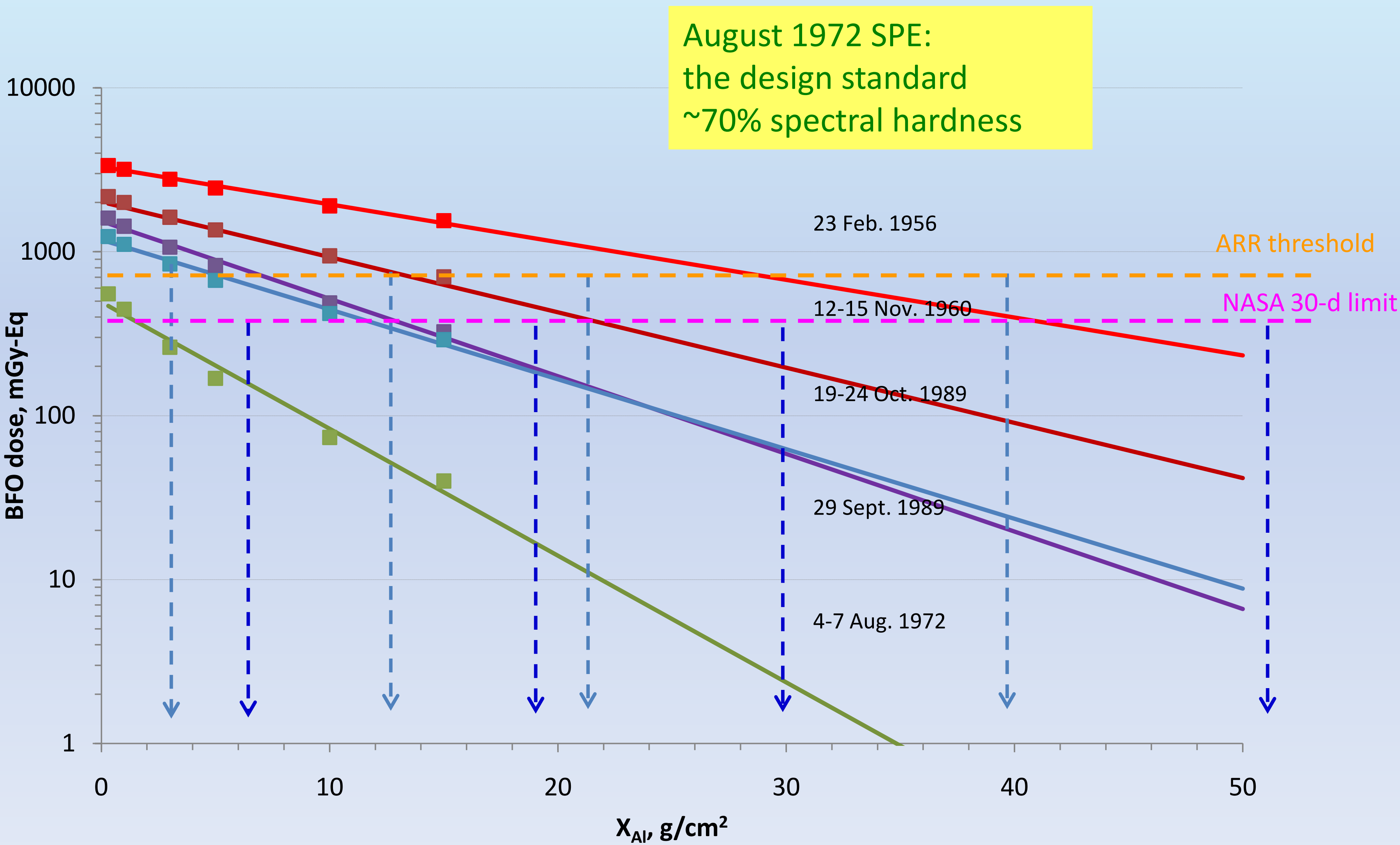
# Proton Spectra of the Carrington Event with Various Band Function Fits



# BFO dose of Male for 180-d Interplanetary Space the Upper 95% Fluence with GLE SPE Spectra



# BFO dose for Males during a 180-d Lunar Mission Upper 95% Fluence with GLE SPE Spectra



# Concluding Remarks

- Band Function Fit for Ground-Level Enhanced (GLE) SPEs:
  - Smoothly rolled one to the other power-law functions:
    - Spectral index at low energies from satellite data
    - Spectral index at high energies from NM data
  - Accurate spectral representation of event-integrated integral fluence:
    - Band function fit based on the combined data from ~10 MeV to ~ 10 GeV
    - Conventional representations made using on-board satellite detectors up to ~100 MeV

Accurate knowledge of the proton fluences and event-integrated differential energy spectra is applied for the radiation analysis of 5 GLE SPEs.

- Comparison of spectrum and effective dose with 3 Functional forms for 5 GLE SPEs : The spectral determination by exponential/Weibull extrapolation in proton energy underestimates the actual proton spectrum above 100 MeV.
  - 23 Feb. 1956 SPE:
    - Overestimated proton fluence and the resultant higher effective dose in exponential spectrum.
    - Weibull and Band functions agree well with each other.
  - 12-15 Nov. 1960 SPE:
    - Higher effective dose at thin shielding by overestimated low energy proton fluence in Weibull function decreases faster at thick shielding by underestimated high energy proton fluence.
  - 4-7 Aug. 1972 SPE:
    - Overestimated King spectrum at 60-200 MeV (IMP series of spacecraft : systematically higher rate of an instrument of > 60 MeV channel on IMP8).
    - Lower effective dose in Band function spectrum, because the decrease in fluence at 60-200 MeV outweighs the increase above ~300 MeV.
  - 9/29-10/2 1989 SPE and 19-24 Oct. 1989 SPE:
    - Qualitatively the same effective dose with three spectral forms, because small decrease in fluence at 60-200 MeV compensates the increase above ~300 MeV in Band function spectrum.

- Radiation dose assessments with spectral representation at high energies

  - Proton spectra with spectral representation at high energies:
    Exposure attenuation: Feb. 1956 is the most and Aug. 1972 is the least in the spectral hardness among 5 GLE SPEs studied in the current study.
  - BFO dose during a 180-d mission in interplanetary space:
    - Fluence at median with various GLE spectra: BFO dose within NASA 30-d limit, with no ARR symptom.
    - Fluence at upper 95% (near the Carrington event) with various GLE spectra: More than 15 g/cm$^2$ shielding required for the Carrington-like event size with 4 spectral hardness of GLE SPEs except the Aug 1972.
  - Exposure to upper 95% fluence with various GLE spectra during 180-d lunar mission: Radiation dose is dependent on total fluence and spectral hardness.
    - No threat to astronauts from large fluence at the upper 95% level with a relatively soft spectrum of Aug. 1972 SPE.
    - Threat to astronauts from the same fluence with harder spectra, such as Feb. 1956 SPE.

# Result

Shielding Requirement during 180-d Lunar Mission
Against the Upper 95% Fluence with Various GLE SPE Spectra

| Spectrum | Aluminum shielding requirement , g/cm$^2$ | |
|---|---|---|
| | NASA 30-d limit | ARR |
| Feb. 1956 SPE | 50 | 38 |
| Nov. 1960 SPE | 28 | 20 |
| Oct. 1989 SPE | 17 | 10 |
| Sept. 1989 SPE | 17 | 10 |
| Aug. 1972 SPE | 4 | EVA suit |